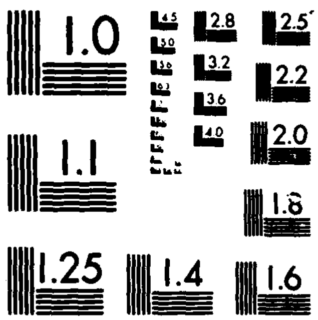
AD-A163 580 STATE-OF-THE-ART SURVEY OF GYROTRON RESEARCH: AN ONRL SPONSORED WORKSHOP(U) OFFICE OF NAVAL RESEARCH LONDON (ENGLAND) P ROMAN 10 JAN 86 ONRL-C-14-85 1/1

UNCLASSIFIED F/G 9/1 NL

END FILMED DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

12

ONRL Report C-14-85

State-of-the-Art Survey of Gyrotron Research: An ONRL Sponsored Workshop

Paul Roman

10 January 1986

U.S. Office of Naval Research, London

SECURITY CLASSIFICATION OF THIS PAGE

AD-A163 580

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release;
distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
C-14-85

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
US Office of Naval Research
Branch Office, London

6b. OFFICE SYMBOL *(If applicable)*
ONRL

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
Box 39
FPO, NY 09510

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)*

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO

11. TITLE *(Include Security Classification)*
State-of-the-Art Survey of Gyrotron Research: An ONRL Sponsored Workshop

12. PERSONAL AUTHOR(S)
Paul Roman

13a. TYPE OF REPORT
Conference

13b. TIME COVERED
FROM ________ TO ________

14. DATE OF REPORT *(Year, Month, Day)*
10 January 1986

15. PAGE COUNT
6

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
09	01	
20	09, 14	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Microwave tubes
Plasmas physics
Plasma accelerators

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The workshop/survey held at King's College, London, UK, on 25 through 26 November 1985 included presentations from the US, the UK, Continental Europe, and the Middle East. This report gives brief coverage of all the presentations, and focusses, in particular, on areas of controversy in both theory and method.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
David L. Venezky

22b. TELEPHONE *(Include Area Code)*
(44-1) 409-4340

22c. OFFICE SYMBOL
01

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

CONTENTS

STATE-OF-THE-ART SURVEY OF GYROTRON RESEARCH: AN ONRL SPONSORED WORKSHOP

1 INTRODUCTION

The London Branch of the Office of Naval Research organized and sponsored in full a specific international workshop on gyrotron research, which took place in London, 25 through 26 November. The invitation-only meeting was generously hosted by the Department of Electronic and Electrical Engineering, King's College. Conference director was Dr. P.A. Lindsay, holder of the Chair for Physical Electronics. There were 19 expert participants of whom six came from the UK, eight from Continental Europe and the Middle East, and five from the US (including two colleagues from NRL). The names, affiliations, and addresses of the participants are given in the Appendix. In addition, we had two distinguished observers. The first, Professor A.L. Cullen, FRS (University College, London), briefly addressed the conferees on behalf of the Royal Society. The second observer was Mr. R.G. Taylor from the UK's Admiralty Research Establishment (Portsdown).

The talks, although well structured, were so designed that maximal audience participation could be assured. For example, despite the tight schedule no attempts were made to cut off talks (as long as they kept to the assigned topic) and unlimited discussion time was guaranteed (in addition to the frequent questions from the floor during the talks). An extensive roundtable session added further opportunities for informal exchanges. The organized social activities (two working lunches and a dinner in a private room of the Faculty Club) led to continued lively discussions as well as to better personal contacts and understanding.

The talks lasted between 25 and 60 minutes, not counting discussions. On request, I can send a copy of the abstract of any selected paper. In addition, the full-length talks, as well as other gyrotron papers solicited from the entire world, including the USSR, will be published in a special issue of the International Journal of Electronics. The guest editors for this publication are Drs. R.K. Parker and A. Fliflet, both at the US Naval Research Laboratory, Washington, DC, who will accept proposed contributions until the end of February 1986.

For the reasons explained in the preceeding paragraph, I will restrict my review to only a very brief general characterization of the presentations.

2 PRESENTATIONS

For the purposes of this report, the presentations may be grouped into five classes, even though no formalized sessions with these titles were arranged; the scheduling, rather, was dictated by practical considerations. The five categories are:

- Overviews
- Special reports
- Technical contributions
- Industry's experiences
- Roundtable session

In many cases the proper placing of a talk is marginal and, by having taken a choice, I do not imply a value judgement.

Naval Research Laboratory)

Overviews

Dr. Parker (US) presented a thorough review of the past history and the current work on fast-wave amplifiers performed at NRL. He explained that current research is directed toward the gyroklystron, the tapered-circuit gyro-travelling-wave-tube, and the ubitron. This selection of device configurations provides a balanced array of performance characteristics. Parker described in detail the gyroklystron and ubitron experiments and compared relative merits and shortcomings. His talk aroused considerable interest among the UK and Continental scientists; many of them appeared to be unaware of these investigations and achievements in characteristics.

Dr. Fliflet (US) described in good detail two current NRL research projects

in the plasma physics division: first ~~he reviewed work~~ on highly relativistic gyrotrons, and then he ~~talked about~~ developments ~~in~~ on the design and initial performance of cyclotron autoresonance masers. Since descriptions of these activities are available in the format of NRL reports, there is no need for me to elaborate.

Dr. Riviere (UK) gave a profound overview of applications of gyrotrons in the area of electron cyclotron resonance plasma heating for fusion experiments. Much of his review focused on research done at the UK's Culham Laboratory, where experiments are conducted under the aegis of the Euratom/UK Atomic Energy Authority Fusion Association. He concluded with the recommendation that high power (around a few MW) machines delivering linearly polarized radiation (which could be sited close to the plasma) should be developed soon; this will be easier than to construct the final, more sophisticated versions with 10 to 50 MW power, remotely sited gyrotrons.

Dr. Hochschield's (West Germany) review was somewhat more specific: he gave a status report on the latest design results of a 150 GHz overmoded gyrotron development project at the German Nuclear Research Institute in Karlsruhe. The purpose ~~of the project~~ is to study higher modes in circular gyrotrons with increasing output power. Presently, they have resonators designed for the TE_{031} mode; in the next stage, work using the TE_{061} mode and complex cavities will be done. Experiments will start in February 1986.

Finally, Dr. Rager (Belgium) gave a comprehensive overview of current and planned gyrotron development studies within the framework of the Fusion Programme of the Commission of the European Communities. This summary served as a good introduction to several specific research contributions presented later on by various participants. We are very appreciative of the European Communities' contribution to the meeting.

Special Reports

In a talk that evoked remarkable interest and spurred unusually lively discussions, Dr. Granatstein (US) discussed his research group's work at the University of Maryland on high peak-power gyroklystron amplifiers. This work is aimed specifically at ~~possible~~ applications to linear accelerators, such as those that could be used in future electron-positron colliders with particle energies over 1 TeV. Gyroklystron amplifiers appear to have intrinsic advantages over conventional klystrons in satisfying the high frequency (optimally 10 GHz), high peak power (100 to 500 MW), and about 100 ns pulse-duration requirements needed for this purpose. The development of a 10 GHz, 30 MW peak power gyroklystron with 1.6 μs pulses is now well under way. The device will have four cavities operating in the TE°_{01} mode. An amplifier efficiency over 38 percent is predicted, with a saturated gain in excess of 50 dB. Several approaches for scaling the peak power to 100 to 500 MW are being studied also. (Use of pulse compression, or TE°_{02} mode cavities with coaxial drift spaces were mentioned in particular.)

The erudite and extensive presentation of Dr. Mourier (France) on results achieved at Thomson-CSF with the development of 100 GHz gyrotron tubes, and future prospects of research, fascinated the audience. So far, four tubes have been tested at 100 GHz. Complex cavities were used; the first one operated in the TE_{02} mode, the second in the TE_{04} mode. The output had, in each case, around 200 kW power; technical difficulties limited the pulse length to 20 ms. Efficiency was 30 percent. Experimental results fully bore out theoretical predictions, except in the area of mode competition.

Two related research reports treated studies in the area of quasi-optical cavity gyrotrons. (Such devices are also studied at NRL and were briefly mentioned in the review talks.) Dr. Tran (Switzerland) described experiments

and progress in the complete assembly of a 200 kW, 100 ms pulse, quasi-optical gyrotron and gyroklyston, operating at 120 GHz, which is being built under the auspices of the European Gyrotron Development Programme by the Euratom--Swiss Confederation Association at Lausanne. He pointed out that the only serious difficulty they encountered was longitudinal mode competition. Plans are to overcome these problems by using selection methods analogous to the employment of diffraction gratings in lasers. Dr. Bondeson took up the problem of radio-frequency space-charge effects in the operation of quasi-optical gyrotrons. Studies at Chalmers University (Göteborg, Sweden) aimed at a theoretical analysis of the problem were carried out by means of an integral equation applied to the case when the gyrocenters are well aligned. The Vlasov equation was the basis of the calculations. In the cases corresponding to the fully non-linear regime operation of both the Lausanne and the NRL experiments, one important prediction is that, ignoring *interactions at higher harmonics*, space-charge effects will have only a very small influence on the particle orbits.

Dr. Lindsay (UK), the chief proponent of the electron ballistic approach to gyrotron theory, gave a fine and convincing presentation in which he extended his previous work on the interplay of five separate electron-bunching mechanisms in gyrotron amplification to the case of gyrotron oscillators. The beamlet-model allows a straightforward calculation of all relevant operational parameters. Experiments done with the 28 GHz, 200 kW Culham Laboratory gyrotron oscillator supported well the calculations in the regime where the assumptions of the theoretical study are valid.

Finally, Dr. Phelps (UK) reported on his recent successful experiments at the University of Strathclyde (Scotland), which determined the mode frequencies of a pulsed electron cyclotron maser, operating in the 26.5 to 40.0 GHz band. As the magnetic field was systematically increased (at low electron beam currents), single modes were observed near the fundamental gyroresonance. The TE_{02}, TE_{61}, and TE_{13} modes were clearly identified. Phelps also gave a general survey of previous experiments with relativistic electron beams at Strathclyde, and pointed out that electron cyclotron maser-type experiments are particularly suited for a university environment because they are inexpensive and simple.

Technical Contributions

A presentation by Dr. Döring (West Germany) described theoretical work done by a small group at the Technical University of Aachen (West Germany). The focus of the talk was on gyrotron efficiency calculations based on a given electric field distribution in the axial direction. The method used is clearly of the ballistic type approach, and it is appropriate for large signals.

In an impressive, well organized and brief address on higher-harmonic gyrotrons Dr. Hirshfield (Israel) reported on past and ongoing work at the Hebrew University of Jerusalem. He pointed out that experiments with single- and two- resonator quasi-optical structures have demonstrated oscillations up through the 4th and 11th harmonics, respectively, for beam energies below 20 keV. A remarkable result was the observation of output at 311 GHz, using a magnetic field of only 14.4 kG. The output was in the 8th harmonic radiation mode. Since theoretical considerations which omit excitation of longitudinal standing modes across the beam cannot explain the observations, the work demonstrates the need for a collective variable theory in certain configurations. Possibility of low voltage, non-superconducting magnet devices, tunable in the submillimeter range were suggested by the results of Hirshfield's group.

In an excellent talk Dr. Dohler (US) reported on some latest developments in the electron ballistic model

theory of gyrotrons at Northrop DSD. One of his major conclusions was that, if space charge effects are taken into account, the ballistic- and the plasma-models give violently disagreeing results for the TE_{om} and TM_{om} gyrotron modes in all harmonics except the basic.

Dr. Edgcombe (UK) summarized work done at the University of Cambridge on the design of space-charge-limited magnetron injection guns, which may be useful for gyrotrons operating with pulse lengths of the order of seconds.

Dr. Thumm reported on his University of Stuttgart (West Germany) group's initial work on high power mode-conversion designs for achieving linearly polarized hybrid electric (HE) mode outputs. The motivation for the work is the potential usefulness of HE gyrotron output for plasma heating and for particle accelerators. So far, the work done is mostly theoretical, but some scaled down experiments have been performed and, in a few cases, demonstrated a remarkable 99 percent conversion efficiency.

Mr. Smith (US) from Thorn-EMI-Varian gave a talk, the content of which was marginally related to gyrotron research. He reported that definitive experiments at his lab finally laid to rest an old controversy: ripple-beam amplifiers cannot work.

Industry's Experiences

The EEV Company, Chelmsford, UK, sponsored several university research groups to develop various types of gyrotrons and other microwave tubes. Mr. Esterson told the meeting that when evaluating the results they came to the conclusion that even if tube feasibility has been demonstrated and the main performance objectives achieved, there are still a number of technological problems and spurious effects which require further investigation and will incur high cost before they are resolved and a useful device can be made. Particular trouble-spots with gyrotrons include collector dissipation, window failure, cathode problems, and mode purity.

Gyrotron oscillator experience at Varian (Palo Alto, California) was discussed in a lively talk by Dr. Jory (US). He recalled the technical difficulties and their eventual circumvention in the small-scale manufacturing of 200 kW continuous wave (CW) gyrotron oscillators at 28, 35, 56, and 60 GHz frequencies, as well as a variety of pulse tubes with the same average energy output and 40 to 100 ms pulse length. Current work aims at developing for limited production a 100 kW CW gyrotron operating at 140 GHz. The cavity uses the TE_{03} mode, but future experiments will involve a $TE_{02,03}$ step cavity.

Roundtable Session

One of the highlights of the workshop was the 2½ hour long roundtable session, chaired by Dr. Riviere (UK). It differed much from the accustomed format of such sessions, because there was no "panel" sitting around a table, but rather, apart from a few introductory remarks made by selected scientists, the "roundtable" involved the entire group of workshop participants.

The session had three topics open for discussion; these were areas that came up during the talks as controversial or not sufficiently explored fields.

Clearly, the most important of these was a comparison of the plasma theory (using mostly the Vlasov equation as the basis of gyrotron operation) with the ballistic electron motion theory (which is based directly on the Lorentz equations of motion). Dr. Dohler came down vigorously on the side of the ballistic theory and mustered arguments of fundamental physical significance to make his standpoint clearer. Dr. Lindsay in his initial remarks compared the mathematical methodologies of the two approaches and emphasized that the ballistic theory--right at the beginning--takes the model of focusing on a single velocity (a delta function approach), whereas the plasma theory also proceeds into this limit, but only at the end of the calculations. Dr. Mourier called attention to the treatment of extreme cases where high currents are involved and pointed out his great successes in

this area with the plasma theory method, though not using the Vlasov equation as a basis of analysis. Other participants emphasized that in the area of space charge waves the two approaches converge, but this does not necessarily support the use of the Vlasov equation as a fundamental tenet of the theory. Dr. Hirshfield observed that in principle, the two basic theories should be equivalent, provided the Vlasov equations could be solved properly (without unwarranted simplifications). The Vlasov approach has been used so frequently that, applying it, one "only has to turn the handle". It is true, he admitted, that this approach is usually not self-consistent, but self-consistency could be achieved, in principle, if all transversal modes were used in the calculations. In his concluding remarks, Dr. Lindsay took a conciliatory approach. He agreed that in certain circumstances it is the plasma theory and in other cases the ballistic theory that is more fruitful in applications. But he maintained that in really tough problems the ballistic approach is more convenient and cost-effective.

Another public discussion was introduced by Dr. Edgcombe who brought up unresolved questions regarding the effect of radio frequency space-charge in gyrotron devices. He talked briefly on some of his recent successful calculations using a dispersion equation to determine the behavior of TE_{om} modes. After several comments and queries, Dr. Mourier clarified the problems by using the plasma-approach.

The third and final topic of the roundtable session consisted of questions addressed by academics to the designer people in the group. Mode purity and power stability were hotly discussed technical problems.

3 CONCLUSION

I believe, the gyrotron workshop was an almost unexpected success, due in large extent to its small size, unusual format, and the determination to ensure an open, honest, lively, and spirited interaction of all participants. Theoretical and experimental reports were well balanced. Likewise, a good proportioning between academics and industrial researchers contributed to a broad view of this important field that has a history of abandoned starts and recent revivals.

A good sense of concensus emerged and cooperation between the top-level participants from eight countries was joyfully evident.

Some enthusiastic participants suggested a repeat-performance next year. Karlsruhe was mentioned as a possible site.

APPENDIX: LIST OF PARTICIPANTS

Belgium

Dr. J.-P. Rager
CEC, Fusion Programme
200 rue de la Loi
B-1049 Bruxelles
Belgium

France

Dr. G. Mourier
Thomson-CSF
BP23
F-78140 Velizy-Villacoublay
France

Israel

Prof. J. Hirshfield
Hebrew University
Racah Institute
Jerusalem
Israel

Sweden

Dr. A. Bondeson
Chalmers University
S-41296 Göteborg
Sweden

Switzerland

Dr. M.Q. Tran
Centre de Recherches en Physique des Plasmas
CH-1007 Lausanne
Switzerland

UK

Dr. C.J. Edgcombe
University of Cambridge
Cambridge CB3 7PR

Mr. M. Esterson
EEV
Chelmsford CM1 2QU

Prof. P. Lindsay
King's College
London WC2R 2LS

Dr. A.D.R. Phelps
University of Strathclyde
Glasgow, G4 0NG

Dr. A. Riviere
Culham Laboratory
Abingdon OX14 3DB

Mr. M.J. Smith
Thorn-EMI-Varian
Hayes, Middlesex

US

Dr. G. Dohler
Northrop Corporation
Rolling Meadows, IL 60008

Dr. A. Fliflet
Naval Research Laboratory
Washington, DC 20375

Prof. V.L. Granatstein
University of Maryland
College Park, MD 20742

Dr. H.R. Jory
Varian Microwave Tube Division
Palo Alto, CA 94303

Dr. R.K. Parker
Naval Research Laboratory
Washington, DC 20375

West Germany

Prof. Dr. H. Döring
Technische Hochschule
D-51 Aachen
West Germany

Dr. G. Hochschield
Kernforschungszentrum
Postfach 3640
Karlsruhe
West Germany

Dr. M. Thumm
Institut für Plasmaforschung
Universität Stuttgart
D-7 Stuttgart 18
West Germany

END

FILMED

3-86

DTIC